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Assessment of the potential and distribution of an energy crop at 1-km resolution from 2010 to 2100 in China – The case of sweet sorghum

Yaoyu Nie[a,b], Wenjia Cai[a,b,*], Can Wang[a,c], Guorui Huang[a,b], Qun Ding[a,b], Le Yu[a,b], Haoran Li[a,b], Duoying Ji[d]

[a] Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing 100084, China
[b] Joint Center for Global Change Studies, Beijing 100875, China
[c] State Key Joint Laboratory of Environment Simulation and Pollution Control (SKLESPC), School of Environment, Tsinghua University, Beijing 100084, China
[d] College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China

HIGHLIGHTS

- Yield per hectare of sweet sorghum are influence by temperature and precipitation.
- Xinjiang and Inner Mongolia are suitable for planting sweet sorghum.
- The 2020 and 2050 biofuel goal can be satisfied by certain scenarios in this paper.
- Climate change and land-use change are critical to energy crop development plan.

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ABSTRACT

Biofuel from energy crops will play an important role in supplying carbon-neutral fuel for the transport sector. However, there are large uncertainties regarding energy crop development and the energy crop potential and distribution need to be evaluated more comprehensively and systematically. In this study, we propose an integrated approach using the AquaCrop model, a geographic information system approach, and a scenario analysis and we conduct a land availability assessment with multiple factors including climate change, land use, soil, topography, regional crop management, and technological improvement to shed light on the potential production, distribution, and temporal-spatial variation of land suitable for sweet sorghum production in China. We evaluate a full range of spatial scales from 1-km resolution to a national assessment in four representative concentration pathways from 2010 to 2100. The results show that most provinces can plant sweet sorghum. The most suitable provinces for sweet sorghum production are Xinjiang, Heilongjiang, Jilin, Inner Mongolia, Yunnan, and Sichuan. The biofuel potential of sweet sorghum in high-slope farmland (0.30–0.73 EJ) and marginal land (11.98–15.18 EJ) can satisfy the biofuel goal in 2020 (0.12 EJ) and 2050 (6.70–8.60 EJ). Climate change and land-use change are critical factors influencing for the current implementation and long-term planning of energy crops in China.

1. Introduction

The 2015 Paris Agreement has proposed to limit the increase in global mean temperatures to well below 2 °C and preferably below 1.5 °C [1]. To achieve these objectives, drastic changes and immediate actions for reducing carbon emissions including applications of large-scale bioenergy projects [2,3] and implementations of negative emission technologies [4] in the energy system should be implemented [5]. As a substitute for coal, oil, and natural gas, bioenergy can reduce carbon emissions that are difficult to reduce, for example in transportation [6], or even result in negative emissions coupled with carbon capture and storage [7]. Compared to other sources of bioenergy, energy crops are not only suitable for large-scale [8] and commercial applications [9] but also can be the main source of newly added biofuels in the coming years [10]. The development of energy crops in the future is determined by critical factors such as environmental

* Corresponding author at: Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing 100084, China.
E-mail address: wcai@tsinghua.edu.cn (W. Cai).

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Table 1
General characteristics of recent studies of energy crops.

Author, year	Objective of study	Spatial coverage	Spatial resolution	Timeframe	Scenario	Yield per hectare	Methodology/Model(s)	Energy crop
Yang et al., 2018 [38]	Growth dynamics and potential	Texas Gulf Coast	site	Current	–	Field experiment	Statistical analysis	Energy cane
Timothy et al., 2018 [20]	Field trial and potential yield maps	United States	site	Multiyear	–	17 poplar trials	PRISM-ELM model	Willow
Qin et al., 2018 [39]	Potentials and impacts	China	1 km	2020	Price scenarios	Statistical data	Land availability and analysis	Miscanthus
Nahm and Morhart, 2018 [40]	Yields and utilization potentials	Virginia, USA	–	2003–2011	–	Origin and ecology traits	Statistical analysis	Virginia mallow
Lee et al., 2018 [41]	Biomass production	USA	1 km	2008–2010	–	Field trials	GIS applications and secondary data	Sorghum, etc.
Gu and Wylie, 2018 [42]	Mapping biofuel potential	Nebraska, USA	0.25 km	2050	A1B	Assumption by scenario	Land suitability assessment	Switchgrass
Sanchez et al., 2017 [43]	Production in surplus lands	Spain	1 km	2010	–	Agro-climatic attainable yield	GIS-based modeling framework	Giant reed
Ozoegwu et al., 2017 [44]	Biomass and bioenergy potential	Nigeria	–	1960–2030	–	Survey data	Statistical sampling, regression analysis	Cassava
Liu et al., 2017 [45]	Potential, economic feasibility	Canada	1 km	Current	–	Statistical data	GIS and economic analysis	Switchgrass, etc.
Xue et al., 2016 [21]	Production potentials on marginal land	China	1 km	–	–	Statistical data	GIS, Monteith radiation model	Miscanthus
Meerbeek et al., 2016 [46]	Bioenergy potential	EU	Provincial level	Current	–	Field study	GIS-based approach	Natura 2000
Saha et al., 2015 [47]	Geospatial bioenergy crop production	Boston, USA	1 km	Current	–	BETY database	GIS-based modeling framework	Miscanthus, etc.
Jiang et al., 2015 [48]	Bioenergy potential on marginal land	Guangxi, China	11 km	Current	–	Statistical data	GIS-based modeling framework	Cassava
Saba et al., 2015 [17]	Potential of bioenergy production	Malaysian	Country level	Current	–	Statistical data	Statistical method	Industrial kenaf
Jiang et al., 2014 [27]	Spatial-temporal variation of the land	China	1 km	1990–2010	–	Statistical data	Geographic analysis	Energy plants
Wang et al., 2014 [49]	Potential to meet energy demand	Great Britain	1 km	Current	–	MiscanFor model	Equilibrium and biogeochemistry model	Miscanthus
Xu et al., 2013 [22]	Geographic distribution and potential	China	1 km	2008	–	Remote sensing data	Land-use model	P. chinensis, etc.
Kuhlman et al., 2013 [50]	Exploring the potential of reed	Netherlands	–	2030	Policy scenario	Statistical data	Production plant siting models	Reed
Nijsen et al., 2012 [23]	Bioenergy potential on degraded lands	Global	10 km	Current	–	Field experiment	IMAGE 2.4, crop growth model	Energy crop
Beringer et al., 2011 [19]	Potential under environmental restrictions	Global	10 km	2010–2100	4 land scenarios	LPJmL DGVM	process-based mode, LPJmL DGVM	Cellulosic crops
Watson et al., 2011 [51]	Potential for sustainable bioenergy	Southern Africa	1 km	Current	–	Statistical data	GIS, analysis of multiple-factors data	Sugarcane
Zhuang et al., 2011 [26]	Bioenergy potential on marginal land	China	1 km	Current	–	Field experiment	Multi-factor analysis method and GIS	Cassava, J. curcas L.
Wit and Faaij, 2010 [52]	Biomass resource potential and costs	EU27, Ukraine	Country level	2030	Yield scenarios	Modeled productivity	Land and economic assessment	Lignocellulosic crops
Bellarby et al., 2010 [53]	Potential distribution of current, future	UK	5 km	2010–2080	B1, B2, A2, A1	Model yield	UK CIP02 model	26 bioenergy crops
Steubing et al., 2010 [54]	Domestic sustainable biomass potential	Switzerland	Country level	Current	–	Statistical data	Bottom-up method	Energy crops, grass
van Dam et al., 2009 [18]	Potential and economic feasibility	Argentina	Provincial level	2015;2030	Scenario A, B, C	Statistical data	Statistical method based on land use	Soybeans, switchgrass
Zhang et al., 2008 [25]	Production potentials	China	1 km	Current	–	Statistical data	GIS, analysis of environmental data, land	Sweet sorghum
Tuck et al., 2006 [55]	Potential distribution of energy crops	Europe	17 km	1990–2080	B1, B2, A2, A1	Statistical data	HadCM3, CSIRO2, PCM and CGCM2	26 bioenergy crops
Hoogwijk et al., 2005 [24]	Potential of biomass energy	Global	55 km	1990–2100	A1, A2, B1, B2	–	IMAGE 2.2	–
Yamamoto et al., 2000 [16]	Scenario analysis of bioresources	Global	–	1990–2100	IPCC IS92a	Assumptions	Global land use and energy model	–

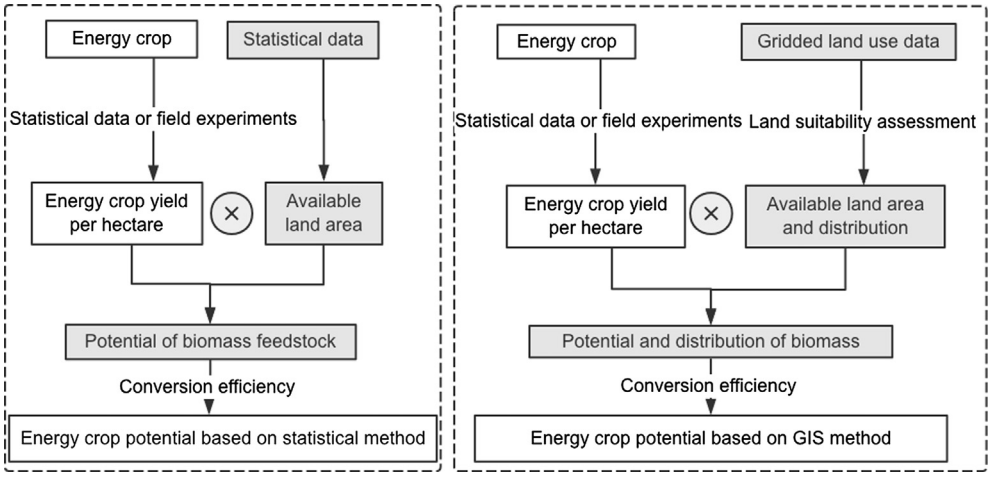
Energy crop
Statistical data
Statistical data or field experiments
Energy crop yield per hectare
Available land area
Potential of biomass feedstock
Conversion efficiency
Energy crop potential based on statistical method
Energy crop
Gridded land use data
Statistical data or field experiments
Land suitability assessment
Energy crop yield per hectare
Available land area and distribution
Potential and distribution of biomass
Conversion efficiency
Energy crop potential based on GIS method

Fig. 1. Flowchart of the two types of methods used for the assessment of energy crop potential.

conditions [11], land use policy [12], and climate change [13]. One concern with energy crops is whether they can meet the biofuel development goals and another concern is how the critical factors influence the potential production and distribution of energy crops. However, few studies have assessed the energy crop potential by considering all of the critical factors. The assessment of the energy crop potential and distribution are of primary importance in the current implementation and development plans of energy crops.

There has been a considerable increase in published studies on the potential and distribution of energy crops in recent years. Yield per hectare and land use are two direct factors that determine the potential and distribution of energy crops. According to data on yield per hectare, land use, and methods, existing studies, can be divided into two main categories, i.e., statistical methods and Geographic Information System (GIS) methods (Table 1). The methodology used in these studies is shown in Fig. 1.

(1). Statistical method. The potential was assessed using the available land area based on statistical data and yield per hectare from field experiments [14]. For example, Reddy et al. [15] estimated the potential of sweet sorghum for bioethanol production by evaluating the yield per hectare and the available land area. Many studies have assessed the potential at the administrative level including the global [16], country [17], and provincial levels [18]. Simplicity, easy implementation, and reproducibility are the advantages of this method. The disadvantage is that there is a lack of representative statistics on the yield per hectare because energy crops have not been planted at a large scale worldwide. In addition, the yield per hectare is not only determined by temperature and precipitation but also influenced by soil texture and plant habits. Therefore, the yield per hectare from field trials does not represent the yield obtained from other areas.

(2). GIS method. In this method, the potential was assessed based on yield per hectare and gridded land use data. Assessment studies of the potential have been able to approximate the actual conditions of energy crops through land use scenarios [19,20,21] or land use models [22,23,24]. Zhang et al. [25] and Zhuang [26] estimated the potential of sweet sorghum and potato in China. Jiang et al. [27] evaluated the spatial-temporal variation of marginal land suitable for energy crops from 1990 to 2010 in China. One of the advantages of a GIS method is that environmental conditions, land suitability, and land variability can be taken into consideration [16,25]. Using GIS-based land-use scenarios or models with assumptions such as food security [28], environmental constraints [19], and sustainable development [29], researchers have determined the spatial distribution of suitable land and the potential production [30]. The other advantage of a GIS method is that it can also provide the production factors at the regional and local levels.

There are large uncertainties in the implementation of energy crops in the future. The potential and distribution are influenced by many factors that affect the land suitability and yield per hectare. Among these factors, climate change and land use change are two of the most critical factors for energy crops from 2010 to 2100 [31,32]. The analytic hierarchy process, agricultural ecology zoning, and multi-factor integrated assessment are the three main methods used currently for land suitability assessment [33]. The multi-factor integrated assessment possesses the advantages of flexibility and suitability and allows for the selection of assessment indicators based on the characteristics of the energy crop. Zhang et al. [25] used the method of multi-factor integrated assessment to assess the potential and suitable areas for distribution of sweet sorghum according to the natural environmental conditions and the plant's characteristics.

To assess the potential production and spatial distribution of energy crops more comprehensively and systematically in China, high-resolution data are needed and the GIS method is a suitable approach. A major disadvantage of GIS methods is that the yield per hectare of the energy crop is difficult to obtain at the regional level. The other disadvantage is that the land suitability does not take into account the impacts of climate change and land use change. In this research, we propose a new approach to integrate the AquaCrop model, a GIS method, and a land suitability assessment to address these problems. We use a large number of fine-resolution datasets and consider several factors and scenarios for a systematic analysis across a full range of spatial scales from 1-km resolution to a national assessment. The AquaCrop model is used for regional yield per hectare simulation and a GIS-based land suitability assessment is used to determine the potential and distribution of energy crops while taking into account the temporal-spatial influence of land-use change and climate change on land suitability.

The Chinese government has declared that the development of energy crops should not compete with farmland and threaten food security [34,35]. Sweet sorghum was selected as the representative non-grain energy crop for biofuel production in China in this study due to its advantages and characteristics such as high biomass yield, drought and cold resistance, flood resistance, wide adaptability, and high sugar content [36,37]. A series of scenarios for sweet sorghum planting including land use and irrigation scenarios were evaluated under four representative concentration pathways (RCPs).

The remainder of this paper is organized as follows. In Section 2, the methods are described. In Section 3, the potential and spatial distribution of sweet sorghum, which are critical for the current

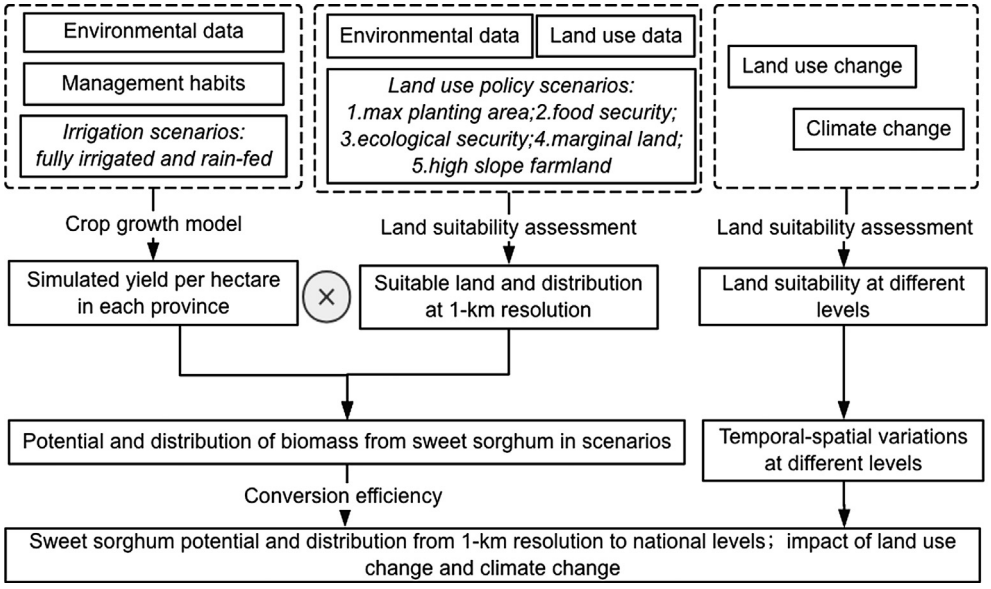
Environmental data
Management habits
Irrigation scenarios: fully irrigated and rain-fed
Environmental data
Land use data
Land use policy scenarios: 1.max planting area;2.food security; 3.ecological security;4.marginal land; 5.high slope farmland
Land use change
Climate change
Crop growth model
Land suitability assessment
Land suitability assessment
Simulated yield per hectare in each province
Suitable land and distribution at 1-km resolution
Land suitability at different levels
Potential and distribution of biomass from sweet sorghum in scenarios
Temporal-spatial variations at different levels
Conversion efficiency
Sweet sorghum potential and distribution from 1-km resolution to national levels; impact of land use change and climate change

Fig. 2. Flowchart of the method used in this research.

implementation of bioenergy are described and the temporal-spatial variation resulting from climate change and land-use change are also elaborated on. The uncertainty analysis and advice for energy crop development are discussed in Section 4. Section 5 provides the conclusions of this research.

2. Methods and materials

Fig. 2 shows the flowchart of the method used in this research. The details of the methods and materials are described in the following five sections. First, we describe the simulation to obtain the yield per hectare at the provincial level. Second, we discuss the land suitability assessment of sweet sorghum at 1-km resolution. Third, we describe the scenario analysis of the land use policy and yield per hectare. Forth, we elaborate on the potential estimation based on the suitable land and simulated yield per hectare. Finally, the temporal-spatial variations influenced by land-use change and climate change are shown at different levels.

2.1. Yield per hectare simulation

AquaCrop is a newly developed Food and Agriculture Organization (FAO) growth model driven by water input. It has been validated and applied by the scientific community at the field and regional levels and strikes a good balance between simplicity, accuracy, and robustness [56]. In this research, the AquaCrop model is used to simulate the yield per hectare at the provincial level in China by using daily meteorological data in four RCPs from 2010 to 2100. The yield simulation can be expressed by the following equation:

$$Y_i = ES \cdot HI_i \cdot K_i \cdot WP_i \cdot \sum \frac{Ta}{Tp} \quad (1)$$

where Y_i represents the yield per hectare in province i, ES (exterior stress) is the coefficient accounting for all exterior stress determined by a default value in the model and influenced by parameters such as fertilization and technical improvement. HI (harvest index) is the harvest index related to time of seeding, flowering, and harvest, K is the coefficient for air temperature stress related to the input data of temperature; $WP$is the normalized water-productivity parameter adjusted for the RCP scenarios and related to precipitation and irrigation; Ta is the daily crop transpiration and Tp is the reference evapotranspiration, and both are default coefficients for sweet sorghum in the model [57,58].

2.2. Land suitability assessment of sweet sorghum

The Chinese environmental protection policies and researcher such as Lu et al. [59] have proposed the following minimum natural environmental conditions for growing sweet sorghum: (1) the accumulated temperature above 10 °C is greater than 2500 °C; (2) the sand content of the soil is below 85%; (3) the upper limit for the slope of the planting area is 25°. In this study, only the minimum environmental conditions are taken into consideration to evaluate the potential distribution of sweet sorghum while disregarding other factors such as environmental impacts, cost, and energy consumption. The suitability of the land is classified based on soil texture, terrain slope, temperature, and precipitation as shown in Table 2. The land suitability is a function of the indicators defined in Eq. (2). The suitable land area can be calculated using Eqs. (2), (3), (4), and the information in Table 2.

$$LS = f(AT \cdot Pr \cdot Sp \cdot St) \quad (2)$$

$$F(LS_{ij}) = \begin{cases} 0, & if \quad LS_{i,j} = 0 \\ 1, & if \quad LS_{i,j} > 0 \end{cases} \quad (3)$$

Table 2
Classification of land suitability for sweet sorghum planting in China.

Level	Value	Slope when sand proportion in soil < 85%	Precipitation when AT above 2500 °C (mm)
Unsuitable	0	> 25%	0
Barely suitable	< 1–4	< 15–25%	0–200 or > 1500
Moderately suitable	< 4–8	< 10–15%	200–400
Highly suitable	< 8–12	< 5–10%	400–1000
Perfectly suitable	< 12–20	0–5%	1000–1500

$$A_i = \sum_{j=1}^{n} A_{i,j} * F(LS_{i,J}) \quad (4)$$

where LS represents the land suitability and is the value in Table 2 as determined by the factors calculated using Eq. (2). LS_{ij}indicates the land suitability of grid j at 1-km resolution in province i. AT is the annual accumulated temperature and Pr is the average precipitation for the years. Sp is the slope and St is the soil texture.$F(LS_{i,j})$ is the area of suitable land in grid j and A_i is the total suitable land area in province i. $A_{i,j}$is the suitable area of grid j in province i, and n is the number of suitable land in province i. For the land suitability of sweet sorghum, not only the environmental conditions but also environmental constraints, food security, environmental protection, technical feasibility, and implementation feasibility are considered; these factors are explained in the scenario analysis section.

2.3. Scenario analysis

Three types of scenarios are investigated in this study (Fig. 2). First, the four RCP scenarios used by the Intergovernmental Panel on Climate Change (IPCC) for its Fifth Assessment Report represent the basic scenarios of the land-use data and meteorological data from 2010 to 2100 [60,61]. Second, two irrigation scenarios, fully irrigated and rain-fed, are used to determine the impacts of the water-productivity parameter on the yield production in the model simulation. The fully irrigated scenario means that sweet sorghum is provided with as much water as required for its growth process by irrigation. The rain-fed scenario [62,63] means that the water is supplied only by precipitation with the value of irrigation set to 0. Third, based on environmental, food, and land constraints [64,65], five land use policy scenarios for sweet sorghum planting are formulated:

(1). The maximum planting area scenario is defined as a theoretical potential. It assumes that all possible lands suitable for the energy crop should be used to plant sweet sorghum. This scenario is intended to provide a theoretical maximum range of the bioenergy potential.
(2). The food security scenario reflects that the energy crop plantings should not occupy arable land to avoid competition with grain production. This scenario is driven by assumptions such as the high demand for food and limited productivity gains in food production.
(3). The ecological security scenario means that bioenergy production should comply with the principles of food security and nature conservation. Therefore, the environmental protection areas should not be identified as areas for the food security scenario.
(4). The marginal land scenario is defined based on the assumption that energy crops can only be planted on marginal lands. This scenario has a higher emphasis on sustainable farming practices and the maintenance of biodiversity. The marginal land scenario represents the technical potential under current technological possibilities.
(5). The high-slope farmland scenario means that only farmland with slopes greater than 15° can be used for energy crop production. Agricultural activities on these lands can lead to soil erosion and even soil degradation; therefore, the Chinese government has developed policies to convert high-slope farmland to other land uses. Compared to other agricultural activities, planting sweet sorghum on high-slope farmland causes less soil erosion with less planting intensity. The high-slope farmland scenario is most consistent with the actual implementation of sweet sorghum.

All the scenarios used in this research are shown in italics in Fig. 2.

2.4. Potential estimation

Based on the simulated yield production and suitable land area, we can obtain the productivity potentials P_i and P_t shown in Eqs. (5) and (6).

$$P_i = Y_i \cdot A_i \quad (5)$$

$$P_t = \sum_{i=1}^{34} Y_i * A_i \quad (6)$$

where P_i is the potential of the biomass production in province i and P_t is the total production potential for 34 provinces in China.

Because the planting and utilization of sweet sorghum for bioethanol production are still in the pilot phase at present [66], the energy efficiency of the production techniques may change in the future. Therefore, we use joule as the unit of the final potential of sweet sorghum production as shown in Eq. (7). P_J is the total potential in the unit of joule in China, C is the utilization ratio of the dry biomass of sweet sorghum, U is the conversion rate from biomass to standard coal, and E is the calorific value of standard coal.

$$P_J = P_t \cdot C \cdot U \cdot E \quad (7)$$

2.5. Data sources and data pre-processing

Three main data sources are used in this study; the first is used for the yield simulation in the AquaCrop model, the second is used for the land suitability assessment, and the third is used for determining the temporal-spatial variation influenced by climate change and land use change.

The first data type includes daily meteorological data from 2010 to 2100 for the four RCPs obtained from the Beijing Normal University Earth System Model (BNU-ESM) scenario. The information related to exterior stress, harvest index, and soils at the provincial level is referenced from the related literature.

The second data type is 1-km resolution grid data of meteorology, soils, and slope, which was derived from the 1:100,000 dataset provided by the Data Center for Resources and Environmental Sciences (RESDC) at the Chinese Academy of Sciences (CAS) (http://www.resdc.cn). The meteorological data is called the Spatial Interpolation Data of Meteorological Elements in China. The 1:100,000 soil data was produced by the second national soil survey. The slope data is derived from the Digital Elevation Model (DEM) of China.

The third data type is 1-km resolution grid land-use data for the RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 scenarios from 2010 to 2100; these data are derived from the 30-m resolution global land-cover maps using Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data and are provided by the Department of Earth System Science at Tsinghua University [67]. The meteorological data (0.44° × 0.44°) to assess the impact of climate change on land suitability are derived from the Coordinated Regional Climate Downscaling Experiment (CORDEX) [68]. All the data and information used in this research are listed in Table 3.

3. Results

3.1. Simulation of yield per hectare of sweet sorghum

Using the simulation results of yield per hectare in the rain-fed scenario in 2010 as a benchmark and on the basis of the four indices including range and change rate of yield per hectare, the change rate between the rain-fed and fully irrigated scenario in the same year, and the trends in the temporal scale in each RCP, we divide the provinces into seven categories as shown in Table 4 and Fig. 3. (1) At the temporal scale from 2010 to 2100, the curves of yield per hectare in categories III, IV, V, VI, and VII exhibit upward trends and those in categories I and II exhibit downward trends. (2) At the spatial scale, different RCP scenarios have different impacts on the yield per hectare. The yield per hectare in category I is constant in RCP 2.6 and decreases in the other three RCPs. The yield per hectare increases in categories IV, V, VI, and

Table 3
Application, resolution, and sources of the data and information used in this research.

Application	Dataset/Information	Resolution	Sources
Yield per hectare simulation	Information related to harvest index	Provincial level	Related literature [69,70]
	Information on exterior stress		Related literature [71]
	Daily meteorological data (2010–2100)		BNU-ESM scenario
Land suitability assessment	Soil data	1 km	RESDC
	Slope data	1 km	RESDC
	Annual precipitation	1 km	RESDC
	Annual accumulated temperature	1 km	RESDC
	Land use data (2010–2100)	1 km	Yu et al. [67]
Temporal-spatial variation	Land use data (2010–2100)	1 km	Yu et al. [67]
	Annual accumulated temperature and precipitation data	0.44° × 0.44°	CORDEX [68]

VII in all four RCPs. (3) RCP 2.6 has the least amount of fluctuation in the yield per hectare and RCP 8.5 has the most fluctuations. (4) The yield per hectare is higher in the fully irrigated scenario than in the rain-fed scenario in each category. In Xinjiang, the yield per hectare is much higher in the fully irrigated scenario (from 36% to 69%) than in the rain-fed scenario. The reason is that the precipitation is much lower in this province than in the other provinces. (5) With regard to the yield per hectare range, Tibet (0–223%) and Qinghai (24–417%) have the largest range because the daily temperature is lower than in the other provinces in the growing season. It is evident that climate change, including precipitation and temperature, as well as different RCP scenarios affect the yield per hectare of sweet sorghum in most parts of China.

3.2. Land suitability for sweet sorghum planting under different scenarios

Fig. 4 shows the trends of the suitable land areas for five land use policy scenarios from 2010 to 2100. The areas are constant in RCP 2.6 and RCP 4.5 and decrease in RCP 6.0 and RCP 8.5 in the maximum planting area scenario. The food security and ecological security scenarios exhibit similar trends; the suitable land area increases slightly in RCP 8.5 and decreases in the other three RCPs. All the four curves decrease in the marginal land scenario. In the high-slope farmland scenario, the suitable land is constant in RCP 6.0 and RCP 8.5, increases up to 2050, is highest in RCP 4.5, and decreases in RCP 2.6. To sum up, there is a negative correlation between the suitable land areas and the RCP scenarios in the long term. This is attributed to urbanization occurring in all parts of the country [72] and climate change influences in the future.

The spatial distributions of suitable land for sweet sorghum planting under different scenarios in 2020 are shown in Fig. 5. In the maximum planting area scenario, we can see that sweet sorghum can grow in all provinces except for Tibet and Qinghai in the four RCP scenarios. With regard to the food security scenario and ecological security scenario, the southern, northwestern, and northeastern areas of China have abundant land resources suitable for sweet sorghum planting. In the marginal land scenario, the suitable land is mostly located in Xinjiang, Inner Mongolia, and Qinghai. In the high-slope farmland scenario, the suitable land is mostly located in the southwestern provinces of China and the land suitability in these provinces is relatively low.

Table 5 shows the ranking of the top three provinces having suitable land for sweet sorghum potential in China. In the maximum planting area scenario, the total area is 686.39–711.51 M ha. Xinjiang (17.60–18.22% proportional change from 2010 to 2100, the same below), Inner Mongolia (16.61–17.22%), and Heilongjiang (6.04–6.30%) are the three top-ranking provinces. In the food security scenario, the range of total suitable land area is 460.25–496.06 M ha and Inner Mongolia (21.35–23.02%), Xinjiang (18.93–20.41%), and Heilongjiang (7.08–7.91%) rank in the top three provinces in terms of the area. In the ecological security scenario, the suitable land area range is 377.78–415.77 M ha and the top three ranking provinces are Xinjiang (20.75–22.23%), Inner Mongolia (18.69–20.01%), and Yunnan (5.54–5.97%). In the marginal land scenario, the suitable lands are located mostly in the northwest of China and the range is 91.49–102.09 M ha with Xinjiang (48.18–49.47%) and Inner Mongolia (18.82–19.67%) ranking as the top two and Gansu and Qinghai (8.75–9.59%) in third place. In the high-slope farmland scenario, the suitable land area range is 1.76–3.93 M ha and Sichuan (34.90–39.87%), Yunnan (29.00–39.28%), and Tibet (10.46–16.48%) are the three top-ranking provinces.

3.3. Temporal-spatial variation of suitable land influenced by climate change

Fig. 6 shows the temporal-spatial variation of suitable land influenced by climate change from 2010 to 2100. There are two types of

Table 4
Categories for the provinces based on the simulation results of yield per hectare.

Category	Provinces (Abbreviation)	Yield per hectare		Change rate between rain-fed and irrigation/ %	Trends of yield per hectare			
		Range/t	Change rate/%		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
I	Beijing (BJ), Tianjin (TJ), Hebei (HEB), Liaoning (LN), Shanxi (SHX), Shan'xi (SX)	24–30	[−10, 10]	0–1	→	↘	↘	↘
II	Shandong (SD), Henan (HEN), Chongqing (CQ), Guizhou (GZ), Guangxi (GX), Guangdong (GD), Hainan (HN), Hunan (HUN), Jiangxi (JX), Hubei (HUB), Anhui (AH), Zhejiang (ZJ), Jiangsu (JS), Fujian (FJ), Yunnan (YN)	21–29	[0, 8]	0–1	↗	↗	↗	→
III	Jilin (JL), Inner Mongolia (NMG), Heilongjiang (HLJ)	20–30	[0, 42]	0–1	↗	↗	↗	↘
IV	Ningxia (NX), Gansu (GS), Sichuan (SC)	15–32	[0, 66]	0–1	↗	↗	↗	↗
V	Qinghai (QH)	2–21	[24, 417]	0–1	↗	↗	↗	↗
VI	Tibet (XZ)	4–25	[0, 223]	0–10	↗	↗	↗	↗
VII	Xinjiang (XJ)	15–30	[0, 91]	36–69	↗	↗	↗	↗

Notes: "↗" means upward trend, "→"means constant trend, "↘" means downward trends.

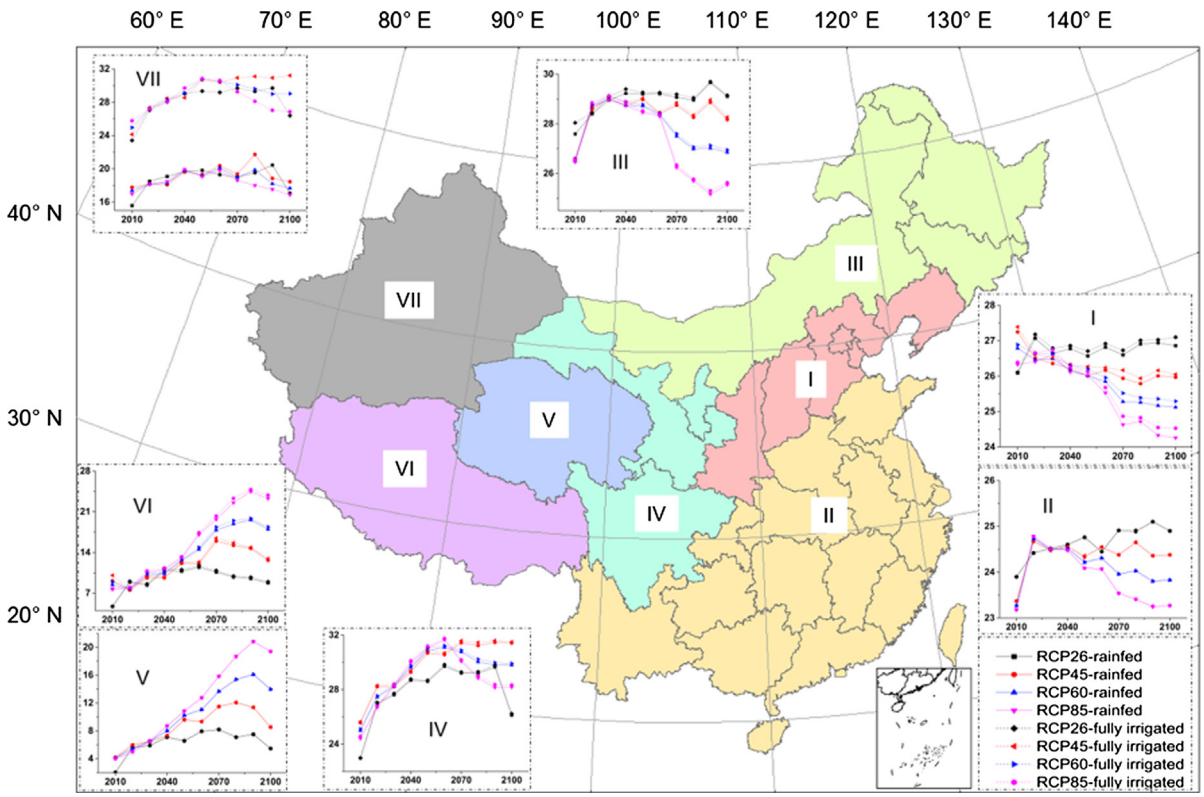

Fig. 3. Yield per hectare for sweet sorghum and trends in each category from 2010 to 2100 in China.

land suitability variations observed in this figure. The first type is unsuitable land that is converted into suitable or suitable land becoming unsuitable under the influence of climate change. Eastern Inner Mongolia and northern Heilongjiang are two regions strongly affected by this type of land suitability variation. In RCP 4.5, the area of suitable land first increases from 2010 to 2030 and then decreases from 2030 to 2100 in both regions. In RCP 8.5, the area of suitable land increases from 2010 to 2100 in both regions. The second type represents an increase or decrease in land suitability and only scales of land suitability change. These land suitability variations occur mostly in western Inner Mongolia, east of Xinjiang, and in parts of Guangdong, Guangxi, Sichuan, Fujian, Jiangxi, and Hunan.

3.4. Temporal-spatial variation of suitable land influenced by land use change

Fig. 7 shows the temporal-spatial variation of land suitability from 2010 to 2100 at 1-km resolution. It is evident that there is an observable change in the suitable land that is influenced by land use change for sweet sorghum from 2010 to 2100 in each RCP scenario in China. In RCP 2.6, Tibet (land suitability area increase is 1.30 M ha, land suitability area decrease is 1.34 M ha, the same as below), Xinjiang

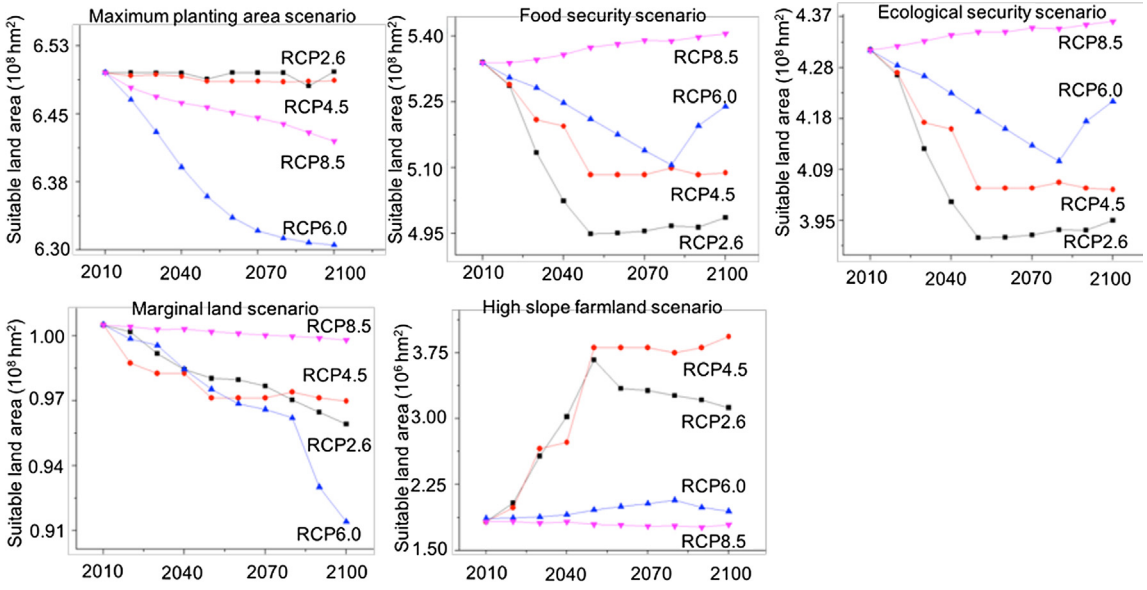

Fig. 4. Areas of land suitable for sweet sorghum for multiple land-use scenarios from 2010 to 2100.

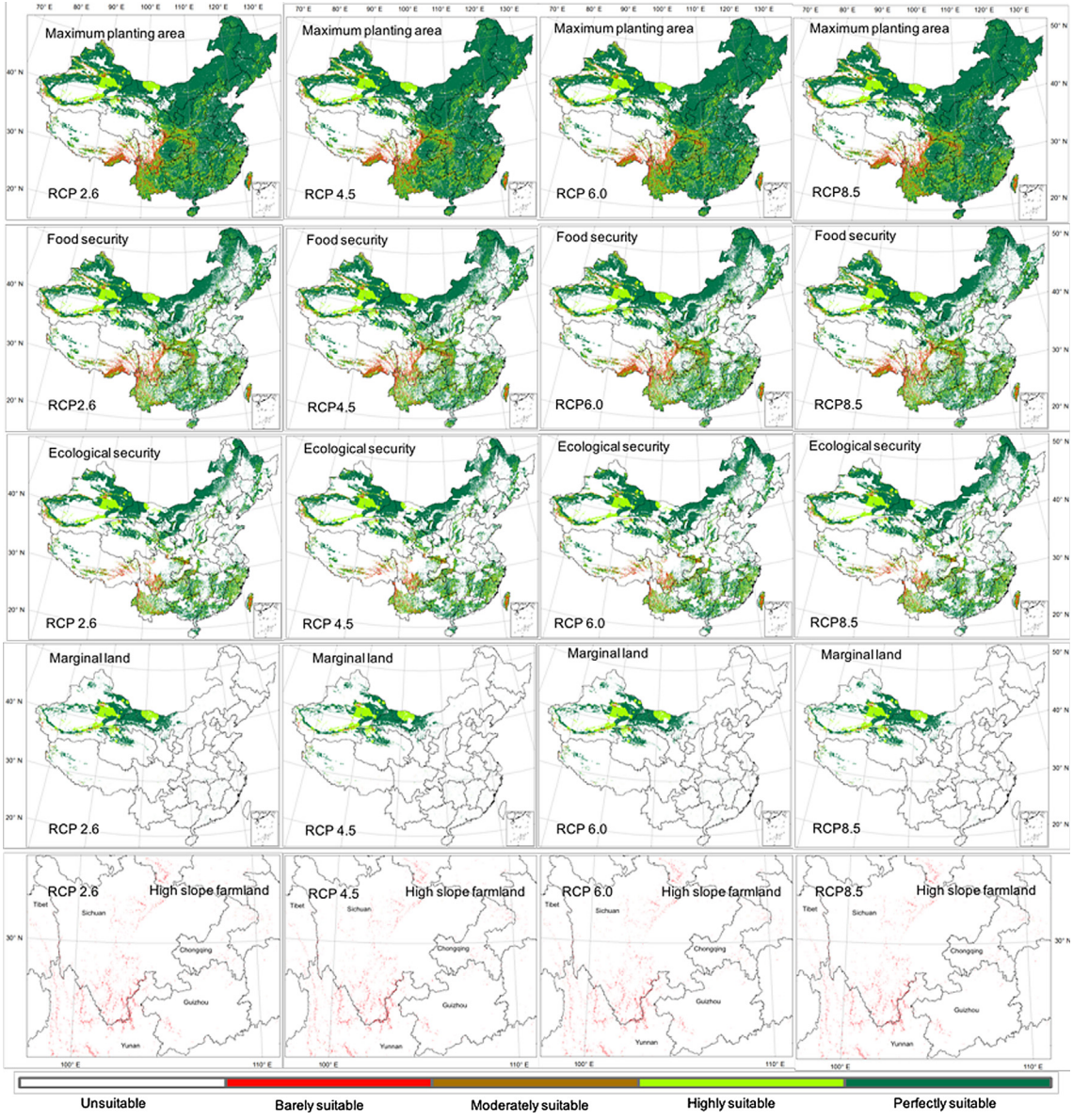

Fig. 5. Land suitability assessment under different scenarios for sweet sorghum planting in 2020.

(1.07 M ha, 1.05 M ha), and Shandong (0.96 M ha, 0.93 M ha) are the three top-ranking provinces. Tibet (1.28 M ha, 1.28 M ha) Xinjiang (1.00 M ha, 1.01 M ha), and Inner Mongolia (0.62 M ha, 0.72 M ha) are the three top-ranking provinces in RCP 6.0. Tibet (1.34 M ha, 1.35 M ha), Xinjiang (1.07 M ha, 1.11 M ha), Shandong (0.72 M ha, 2.36 M ha), Hunan (0.73 M ha, 1.30 M ha), Henan (0.72 M ha, 2.01 M ha), Jiangsu (0.4 1 M ha, 1.24 M ha), Guangdong (0.41 M ha, 1.01 M ha), and Hebei (0.56 M ha, 2.04 M ha) are the provinces exhibiting the greatest changes in RCP 8.5. Overall, there are more areas of decrease than areas of increase (Fig. 7).

Fig. 8 shows the areas of change (sum of the areas of increase and decrease in land suitability) and the percent land use change (ratio of changed area to total land area) from 2010 to 2100 at the municipal level. In general, as shown in Figs. 7 and 8, most of the changes in land suitability influenced by land use change occur in Beijing, Tianjin, Guangdong, Shandong, Henan, Hunan, Hebei, and Jiangsu where urbanization is prevalent. Changes also occur in Xinjiang, Tibet, Heilongjiang, and Inner Mongolia because these areas are sensitive to

Table 5
Ranking of the top three provinces having suitable land for sweet sorghum potential in China.

Land use policy scenario	Maximum planting area	Food security	Ecological security	Marginal land	High-slope farmland
Total suitable area (M ha)	686.39–711.51	460.25–496.06	377.78–415.77	91.49–102.09	1.76–3.93
Ranking 1	XJ	NMG	XJ	XJ	SC
Proportion (%)	17.60–18.22	21.35–23.02	20.75–22.23	48.18–49.47	34.90–39.87
Ranking 2	NMG	XJ	NMG	NMG	YN
Proportion (%)	16.61–17.22	18.93–20.41	18.69–20.01	18.82–19.67	29.00–39.28
Ranking 3	HLJ	HLJ	YN	GS/QH	XZ
Proportion (%)	6.04–6.30	7.08–7.91	5.54–5.97	8.75–9.59	10.46–16.48

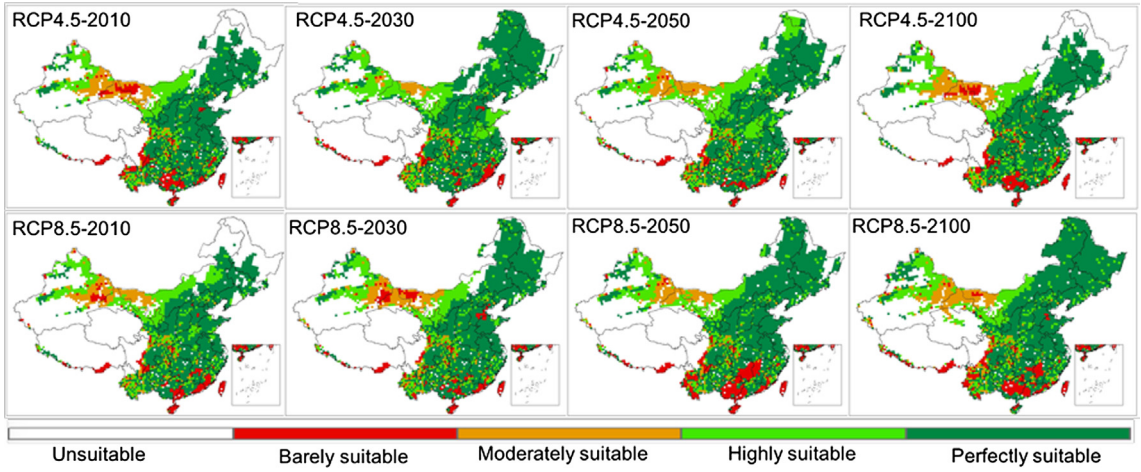

Fig. 6. Temporal-spatial variation of suitable land influenced by climate change.

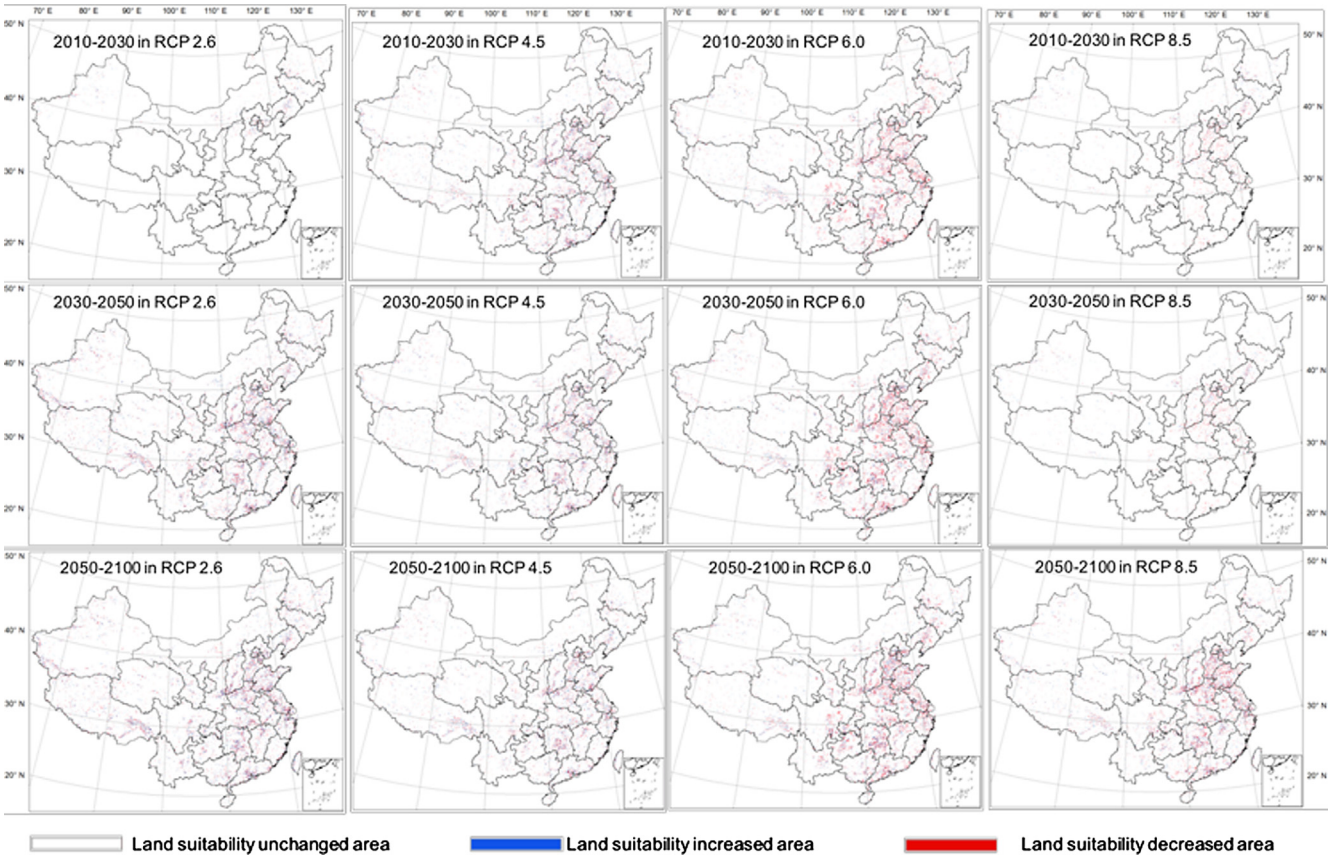
2010-2030 in RCP 2.6
2010-2030 in RCP 4.5
2010-2030 in RCP 6.0
2010-2030 in RCP 8.5
2030-2050 in RCP 2.6
2030-2050 in RCP 4.5
2030-2050 in RCP 6.0
2030-2050 in RCP 8.5
2050-2100 in RCP 2.6
2050-2100 in RCP 4.5
2050-2100 in RCP 6.0
2050-2100 in RCP 8.5
Land suitability unchanged area
Land suitability increased area
Land suitability decreased area

Fig. 7. Temporal-spatial variation of land suitability influenced by land use change at 1-km resolution.

climate change.

In this research, we assume that municipalities make long-term plans for energy crop development only when the percent land use change is small and the land is not sensitive to climate change. The provinces including Beijing, Tianjin, Shanghai, Shandong, Jiangsu, etc. are not suitable for energy crop development whereas the southern and central-west provinces, Inner Mongolia, eastern Xinjiang, eastern Jilin, Heilongjiang, and Liaoning are suitable for the energy crop industry.

3.5. Potential production of sweet sorghum

The potential biofuel production of sweet sorghum from 2010 to 2100 in China is shown in Fig. 9. The potential range is 0.33–0.80 EJ in the high-slope farmland scenario, which can supply the biofuel demand of 0.12 EJ in 2020 proposed by the 13th Five Year Plan for bioenergy development [9]. Compared to the Chinese biofuel goal (6.70–8.60 EJ) in 2050 proposed by the International Institute for Applied Systems Analysis (IIASA) [73], the potential range (12.30–20.46 EJ) in the marginal land scenario can satisfy this goal. Assuming that E10 (gasoline mixed with 10% bioethanol) will be used for transportation nationwide, the demand of bioethanol will be 0.36 EJ in 2017 (the total amount of gasoline consumption is 123 Mt). Therefore, the potentials in the high-slope farmland scenario could only satisfy the fuel demand in RCP 2.6 and RCP 6.0. For the other three land-use policy scenarios that represent the theoretical potential of the energy crop, the potentials range from the lowest value of 61.57 EJ in the ecological security

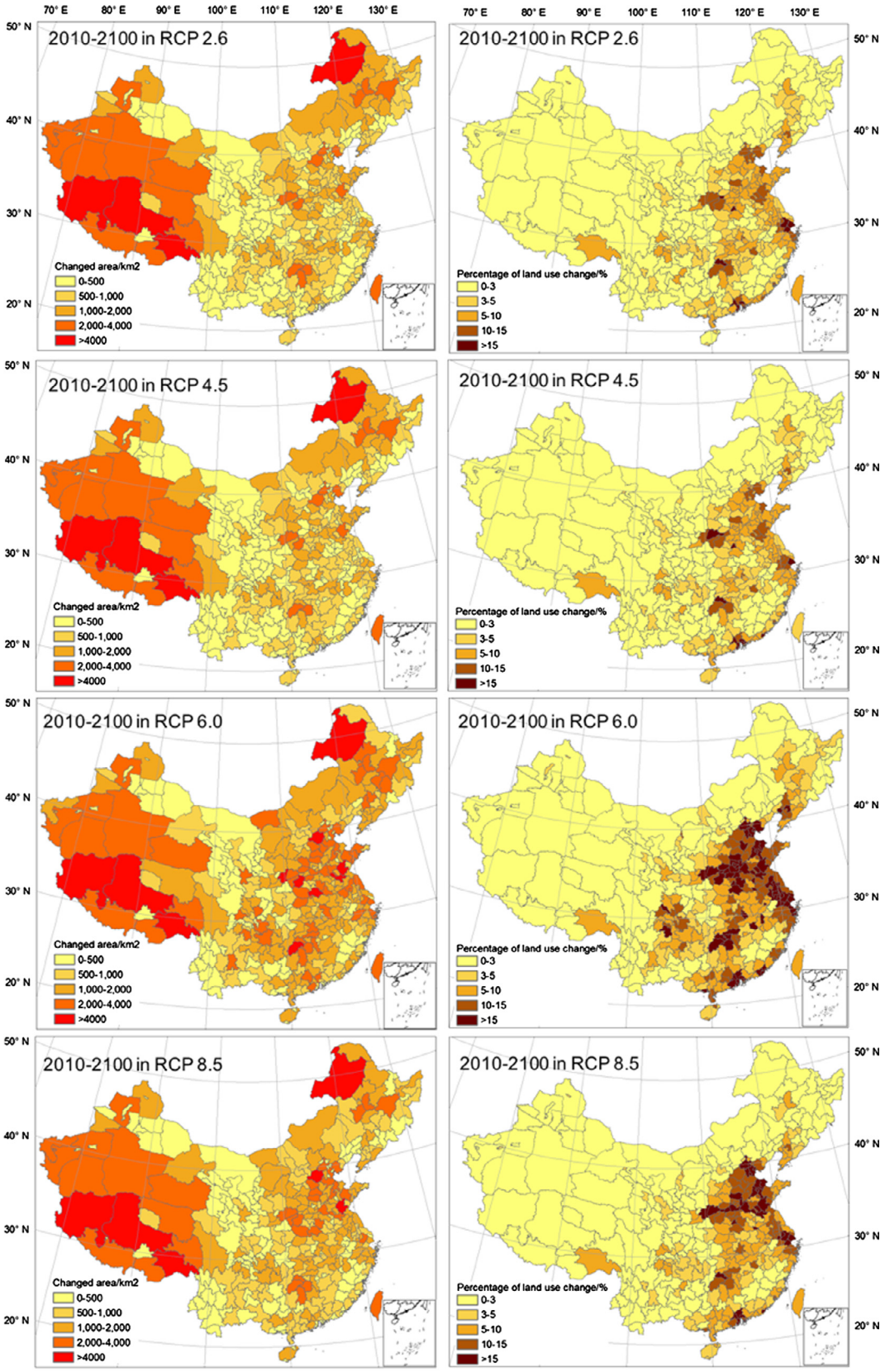

Fig. 8. Temporal-spatial variation of land suitability influenced by land use change at the municipal level.

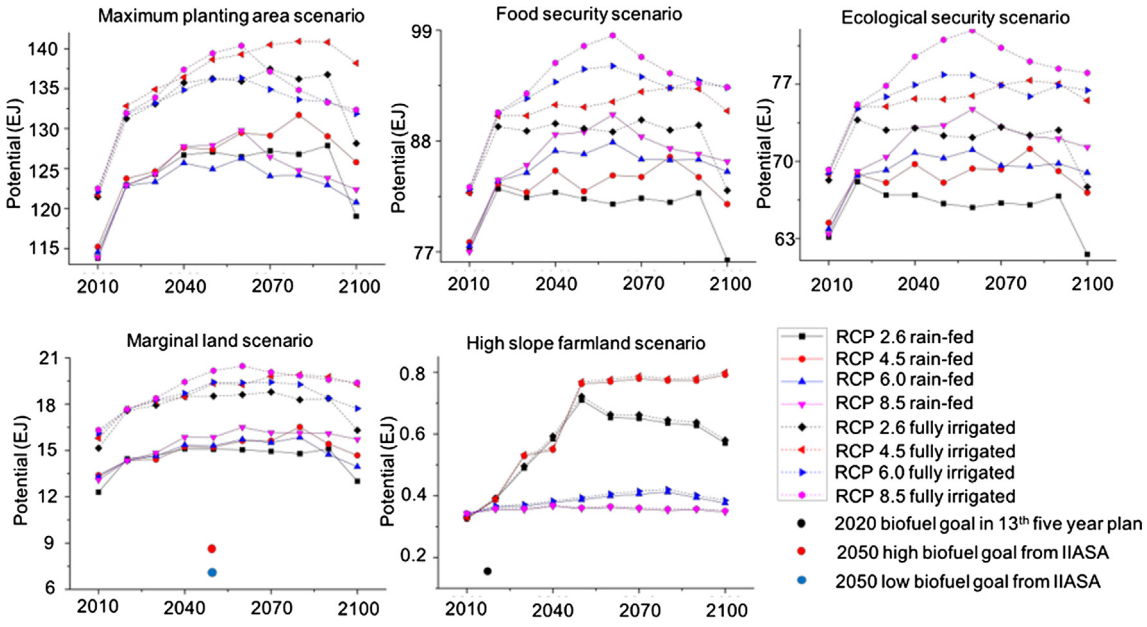

Fig. 9. Potential production of sweet sorghum from 2010 to 2100.

Table 6
Ranking of top five provinces of sweet sorghum potential in China.

Land use policy scenario	Ranking	1	2	3	4	5
Maximum planting area	Province	NMG	XJ	YN	HLJ	SC
	Min/EJ	20.87	14.50	6.81	6.46	5.49
	Max/EJ	26.62	28.93	8.15	9.18	7.32
Food security	Province	NMG	XJ	HLJ	YN	SC
	Min/EJ	18.55	10.72	5.36	4.73	3.37
	Max/EJ	23.63	21.48	7.97	5.78	4.44
Ecological security	Province	NMG	XJ	YN	HLJ	SC
	Min/EJ	13.46	9.83	4.42	3.32	2.98
	Max/EJ	17.21	19.61	5.31	5.07	3.94
Marginal land	Province	XJ	NMG	GS	JX	XZ
	Min/EJ	5.61	3.38	1.09	0.25	0.17
	Max/EJ	11.12	4.31	2.17	0.35	0.91
High slope farmland	Province	YN	SC	GZ	CQ	XZ
	Min/EJ	0.13	0.12	0.09	0.07	0.01
	Max/EJ	0.23	0.42	0.01	0.02	0.07

scenario to the highest value of 140.91 EJ in the maximum planting area scenario. Table 6 shows the sweet sorghum potential range and ranking of the top five provinces in the five land use policy scenarios.

4. Discussion

4.1. Comparison with other studies

Our results show that the suitable area for sweet sorghum ranges from 1.76 to 711.51 M ha in various land use policy scenarios, which is larger than that reported in other studies. The estimates for marginal land areas for large-scale planting in China in other studies were 7.0 M ha [59] and a range from 59 M ha to 380 M ha [25]. The potential production in the Global Energy Assessment Report by the IIASA is 23.10 EJ. Other studies have focused on the marginal land scenario and have reported a range of the potential production of 16.10–19.40 EJ [59]. In contrast, the potential production in this study is 0.33–140.91 EJ in various land use policy scenarios and the potential in the marginal land scenario is 12.30–20.46 EJ. The primary reasons for the differences between our study and other published results are as follows. (1) Different assumptions and scenarios were used. There are three types of scenarios used in this study: four RCPs, five land-use policy scenarios, and two irrigation scenarios. The scenario settings are more comprehensive and systematic than in other studies, meaning that this study can be adapted to various future development conditions. (2) Different datasets were used. The dataset used in this study includes a simulated land-use dataset from other models [71], simulated yield per hectare data from the AquaCrop model, terrain data, soil texture data, and other climate change data. (3)

4.2. Data uncertainties

First, because this research is mostly based on yield per hectare simulations and suitable land assessments from 2010 to 2100, various land use scenarios, simulated yields per hectare, and modeled land-use data can result in uncertainties of the potential production. Second, the results are influenced by the resolutions because 1-km resolution and provincial-level data are used in this study. Finally, due to the availability of the data and information, the impacts of cost-benefit, water stress, energy efficiency, and other problems were not taken into consideration for the conversion of sweet sorghum to biofuel.

The modeling results of yield per hectare are validated by two measures. First, we have collected data for the observed yield per hectare in several provinces from published papers, including Xinjiang, Inner Mongolia, Henan, Guangdong, Shandong, Jilin, and Anhui. A linear regression was performed for the modeled yield per hectare (mean value from 2010 to 2016) and the observed yield per hectare. The R^2 value is 0.7752 and the regression results in all provinces are generally good.

4.3. Production potentials of sweet sorghum for real implementation

In this research, the biofuel potential from sweet sorghum is evaluated based on a theoretical hypothesis. A real implementation should be taken into account when formulating policy for energy crop development. First, Tibet and Qinghai are not suitable for energy crop development because their yield per hectare is much lower. Second, the fully irrigated yield per hectare is higher than the rain-fed one in Xinjiang due to precipitation. To avoid exacerbating the local water stress, rain-fed planting is a better choice for sweet sorghum in Xinjiang. Taking these situations into account, the potential production range would be 0.30–0.73 EJ in the high-slope farmland scenario and

11.98–15.18 EJ in the marginal land scenario; both can satisfy the biofuel development goals for 2020 and 2050.

4.4. Advice on development of energy crops

First, for the recent biofuel development goal, the minimum biofuel potential of Yunnan and Sichuan in the high-slope farmland scenario is larger than the development goal of biofuel (0.12 EJ) in 2020. It is a good choice to plant sweet sorghum in high-slope farmland in Yunnan and Sichuan. Second, for the medium-term development plan (6.70–8.60 EJ) up to 2050, the combined production of Xinjiang, Inner Mongolia, and Gansu in the marginal land scenario is 10.09 EJ. Therefore, Xinjiang, Inner Mongolia, and Gansu are the most suitable provinces for rain-fed sweet sorghum planting. Land with higher suitability could be regarded as a priority area for energy crop development in these provinces. Third, with regard to the long-term development plan up to 2100, on the one hand, climate change is an important factor influencing the yield per hectare. On the other hand, climate change and land-use change affect the suitability and the distribution of land suitable for energy crop planting. More attention should be paid to climate change and land-use change when developing long-term plans. Eastern Xinjiang, western Inner Mongolia, Guangdong, Jiangxi, and Heilongjiang are sensitive to climate change. Beijing, Tianjin, Jiangsu, Shandong, Chongqing, and Henan are sensitive to land-use change. At last, there is ample evidence that the RCPs also have a significant impact on the yield per hectare and the suitable land distribution. More measures regarding energy crops should be taken to handle mitigation.

The novelty of this research is that we proposed a new integrated method to assess the potential and distribution of an energy crop and took into consideration climate change and land use change. The results provide higher spatial resolution data for current energy crop development and practical applications to facilitate the evaluation of the potential and distribution of the energy crop more comprehensively and systematically.

Another novelty of this research is that the potential and distribution of the crop provide scientific evidence to support the development of sweet sorghum as a critical biofuel resource. In addition, the temporal-spatial variations influenced by land use change and climate change are critical for the long-term development of the energy crop. Because sweet sorghum has not been planted widely in China and few energy crops are grown at a large scale worldwide, additional research is required for different aspects, especially the evaluation of costs and benefits, water stress, and public recognition in the near future. Many important open issues will only be resolved as incremental attempts are made to initiate energy crop production and increase the role of biofuels in the energy supply.

5. Conclusions

In this research, we used an integrated framework by combining a crop growth model, land availability assessment, a scenario analysis, and GIS methods to assess the potential and distribution of sweet sorghum in China. Land-use, climate change, soil texture, slope, and other factors were taken into consideration to evaluate the temporal-spatial variation of suitable land. The following conclusions are drawn: (1) The AquaCrop simulation results show that the RCPs, temperature, and precipitation affect the yield per hectare in all provinces. Considering climate change and land-use change from 2010 to 2100 in China, sweet sorghum can be planted in most provinces. (2) When constraints such as food security, environmental protection, and implementation conditions are taken into consideration, the suitable land area is 460.25–496.06 M ha for the food security scenario, 377.78–415.77 M ha for the ecological security scenario, 91.49–102.09 M ha for the marginal land scenario, and 1.76–3.93 M ha for the high-slope farmland scenario. When the yield per hectare and suitable land are taken into consideration, Xinjiang, Inner Mongolia, Heilongjiang, Jilin, Liaoning, Gansu, Sichuan, and Yunnan are the most suitable provinces to plant rain-fed sweet sorghum. (3) The biofuel potential of sweet sorghum is 0.33–0.80 EJ for the high-slope farmland scenario, 12.30–20.46 EJ for the marginal land scenario, 61.57–81.09 EJ for the ecological security scenario, 76.81–98.47 EJ for the food security scenario and 113.79–140.91 EJ for the maximum planting area scenario. When excluding the unsuitable provinces including Tibet, Qinghai, and Xinjiang for the fully irrigated scenario, the potential is 0.30–0.73 EJ for the high-slope farmland scenario and 11.98–15.18 EJ for the marginal land scenario; both scenarios exceed the biofuel development goal for 2020 (0.12 EJ) and 2050 (6.70–8.60 EJ) respectively. However, the demand for bioethanol for transportation fuel (0.36 EJ in 2017) shows that more measures are required in the high-slope farmland scenario. (4) Therefore, first, we propose that the Chinese government should regard the provinces with high potentials as the major development areas for sweet sorghum planting and biofuel production. Second, policymakers should pay more attention to climate change and land-use change when developing medium-term and long-term plans for energy crops.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.01.214.

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